



Study on cold head structure of a 300 Hz thermoacoustically driven pulse tube cryocooler

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ABSTRACT

High reliability, compact size and potentially high thermal efficiency make the high frequency thermoacoustically-driven pulse tube cryocooler quite promising for space use. With continuous efforts, the lowest temperature and the thermal efficiency of the coupled system have been greatly improved. So far, a cold head temperature below 60 K has been achieved on such kind of cryocooler with the operation frequency of around 300 Hz. To further improve the thermal efficiency and expedite its practical application, this work focuses on studying the influence of cold head structure on the system performance. Substantial numerical simulations were firstly carried out, which revealed that the cold head structure would greatly influence the cooling power and the thermal efficiency. To validate the predictions, a lot of experiments have been done. The experiments and calculations are in reasonable agreement. With 500 W heating power input into the engine, a no-load temperature of 63 K and a cooling power of 1.16 W at 80 K have been obtained with parallel-plate cold head, indicating encouraging improvement of the thermal efficiency.

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1. Introduction

High frequency thermoacoustically driven pulse tube cryo-cooler (HFTAPTC) promises remarkable advantages of simplicity, high reliability and potentially high thermal efficiency [1], which might find important space applications. With a better understanding of the key components and coupling mechanism between a thermoacoustic heat engine and a PTC [2,3], the no-load cold head temperature of the HFTAPTC has greatly decreased from 147 K [4] in its debut to below 60 K most recently [5]. However, compared with the PTCs operated around 50 Hz [6], the ratio of output cooling power to input acoustic power of the present HFTAPTC is still very low, seriously restricting its engineering use. Theoretical analyses from Radebaugh and O'Gallagher [7] indicate that the performance of the PTC remains efficient as the operating frequency scales up from 50 Hz to 1000 Hz, which implies that the performance of the current HFTAPTC could be much improved.

In retrospect, the quick development of the PTC in the last two decades mainly benefits from the improvements of phase shifters [8,9]. We have done much work on the phase shifters and regenerators in the 300 Hz system for the past few years. The work presented here focuses on studying the configuration of the cold heat exchangers which is also important. The cold head structure of the low frequency PTC (around or lower than 50 Hz) is generally

made of stacked copper meshes or copper blocks with slots using electrical discharge machining (EDM). While under high frequency operation, the flow channel needs to be very small which either requires much finer screen meshes leading to large viscous loss or it is too difficult to use EDM. To make a compromise between heat exchange and viscous loss, a parallel-plate structure cold head with regular flow channels might be a good candidate for a HFTAPTC.

In this paper, the effects of varying the structures of the cold heads on the cooler performance are numerically investigated in terms of the heating block temperature, the pressure amplitude at the inlet of the PTC, the no-load cold head temperature and the cooling power at 80 K. Then, the effects of varying the dimensions of the parallel-plate cold head are studied experimentally and the comparisons between experiments and calculations are made. Finally, conclusions are drawn. The results are beneficial to the design and optimization of a HFTAPTC.

2. Numerical simulation

In order to investigate the impact of cold head structure on the performance of a HFTAPTC, extensive numerical simulations have been conducted firstly.

Fig. 1 depicts the geometry of the HFTAPTC studied in this work. The HFTAPTC consists of a standing-wave thermoacoustic heat engine (SWTE), an acoustic pressure amplifier tube (APAT) and a PTC. The SWTE is composed of a heating block, a stack, an ambient heat exchanger and a resonator, whose dimensions are listed in Table 1.

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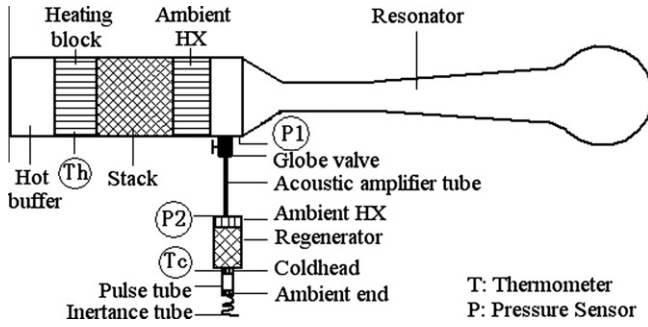


Fig. 1. Schematic drawing of a 300 Hz HFTAPTC.

Table 1
Dimensions of the 300 Hz SWTE.

Section	Dimension
Hot buffer	i.d. 50 mm, length 30 mm
Heating block	i.d. 50 mm, length 20 mm
Stack	i.d. 50 mm, length 80 mm
Room ambient HX	i.d. 50 mm, length 15 mm
Resonator	Mainly 450-mm cylindrical tube + 400-mm tapered tube (29- to 71.8-mm i.d.) + 151-mm i.d. spherical vessel

The APAT is a copper tube coupling the SWTE and the PTC with a fixed diameter of 4.3 mm and a length of 58 mm in this work. The PTC is composed of an ambient heat exchanger, a regenerator, a cold head, a pulse tube, a secondary ambient heat exchanger and a hybrid inertance tube. Table 2 summarizes the dimensions of the PTC.

In the previous design, the cold head is simply a hollow copper tube connecting the regenerator housing to the pulse tube. To have an overview of the effects of the optional cold head structures, 120# stacked copper mesh and three parallel-plate cold heads are taken into consideration in simulations. Table 3 lists the detailed dimensions. The schematic drawing and the assembly drawing of the parallel-plate structure are shown in Fig. 2 respectively. The parallel plate is made with photochemical etching process. Certain number of parallel plates are aligned, stacked and finally soldered to form the parallel-plate cold head.

Thermoacoustic modular program is used to simulate the entire coupled system. Eqs. (1)–(3) characterize the dynamics and energy conversion of the working gas with corrections for the turbulent flow mainly occurring in the resonator and the APAT.

$$\frac{d\hat{p}}{dx} + R_2 \hat{U} = 0 \quad (1)$$

$$\frac{d\hat{U}}{dx} + R_1 \hat{p} - R_3 \hat{U} = 0 \quad (2)$$

$$\frac{dH}{dx} = Q, \quad H = c_1 + c_2 \frac{dT_x}{dx} \quad (3)$$

Table 2
Dimensions of the 300 Hz PTC.

Section	Dimension
Regenerator	i.d. 10 mm, length 30 mm
Cold head	i.d. 6 mm
Pulse tube	i.d. 6 mm, length 40 mm
Inertance tube	i.d. 2 mm, length 300 mm + i.d. 4.3 mm, length 1100

Table 3
Dimensions of the optional cold heads.

Types	Gas–solid heat exchange areas
Hollow tube	37.7 mm ²
Copper mesh	120# mesh, 448.6 mm ²
Parallel plate	
A	183.7 mm ² (channel width 0.15 mm)
B	400.6 mm ² (channel width 0.12 mm)
C	529.1 mm ² (channel width 0.10 mm)

Here, $\hat{p}$, $\hat{U}$ are complex pressure wave and volume flow rate, T_x is the mean temperature of the working gas, H is the total energy including integrated enthalpy flow over the fluid passage cross section and static heat conduction, and Q is the heat input to the gas from outside the system. R_1 , R_2 , R_3 , c_1 , c_2 are complex coefficients which are functions of the fluid passage geometry, frequency, mean pressure, volume flow rate, temperature distribution, etc. The details can be found in Refs. [10,11] and the numeric algorithm can be found in Ref. [12].

For all the calculations, helium gas, a heating power of 500 W input into the heating block of the SWTE and a mean pressure of 4.0 MPa are used.

Table 4 gives the calculated results. Generally speaking, narrower flow channels lead to larger viscous loss. However, the structure of the cold head has almost no influence on the heating block temperature and the pressure amplitude at the inlet of the PTC, which might be attributed to the higher acoustic resistance of the regenerator over that of the cold head.

However, due to the increase in the gas–solid heat exchange area, the heat transfer is greatly enhanced. For the same inlet pressure amplitude, the no-load temperature of the PTC with either mesh or parallel-plate cold head is a bit lower than that of the PTC with hollow tube cold head by about 5–7 K. The calculated lowest no-load temperature reaches 45.3 K with parallel-plate C cold head. There is little difference on the no-load temperature of the PTC with parallel-plate cold heads B and C, indicating that the advantage of increasing the gas–solid heat exchange areas might be undermined by the excessive rise of viscous loss. Moreover, the cooling power benefits much more from the improvement of gas–solid heat exchange areas. On one hand, for the PTC with hollow tube cold head, a cooling power of only 0.42 W is obtained, which is less than one fourth that of the PTC with copper mesh cold head. On the other hand, compared to the stacked copper mesh, the parallel plate has smaller viscous resistance due to regular and smooth flow channels. Consequently, the achievable cooling power of the parallel-plate cold head is larger than that of the copper mesh cold head by at least 10%. A largest cooling power of 2.18 W at 80 K is attained on the PTC with parallel-plate cold head C.

The calculated results are encouraging as the cooling power could be greatly improved with the use of parallel-plate cold head.

3. Experiments and discussions

3.1. Experimental apparatus

In order to validate the calculations, lots of experiments have been carried out. The dimensions of the experimental setup are the same as used in the simulations. Due to the difficulty in soldering the stacked copper mesh, only parallel-plate cold heads A–C are chosen for comparisons between calculations and experiments. Pressure, temperature and cooling power measurements are conducted and the corresponding sensors are disposed as shown in Fig. 1. Pressure sensors PCB are placed at the outlet of the SWTE

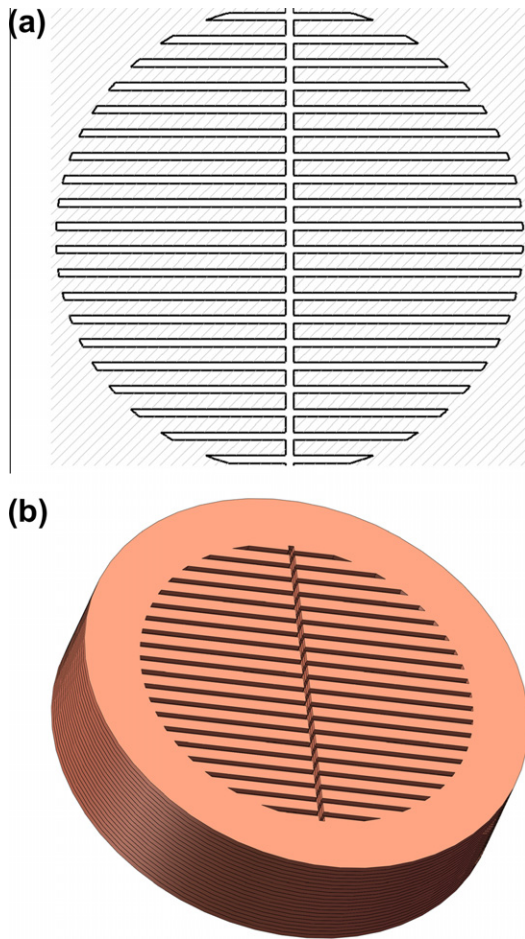


Fig. 2. Schematic and assembly drawing of the parallel plate structure. (a) Schematic drawing; (b) assembly drawing.

Table 4
Calculated results, 4 MPa helium and 500 W heating power.

Types	P_2 (MPa)	Th (K)	No load Tc (K)	Qc@80 K (W)
Hollow tube	0.393	883.1	52.1	0.42
Copper mesh	0.392	886.3	48.5	1.76
Parallel-plate A	0.404	864.5	46.8	1.90
Parallel-plate B	0.407	864.3	45.6	2.07
Parallel-plate C	0.408	862.1	45.3	2.18

and the inlet of the PTC to measure the local pressure waveforms. Sheathed K-type thermocouple Th and calibrated platinum resistance thermometer Tc are used to measure the solid temperatures at the heating block and the cold head respectively. Additionally, cooling power is measured through a film resistor powered by a DC source and detected by an Agilent digital multimeter with four-wire method. Finally, all the signals are manipulated by Lab-view programs [13].

3.2. Experimental results and discussions

In accordance with the simulations, 4.0 MPa helium gas and a heating power of 500 W are applied in the experiments. Besides the pressure amplitude and temperature under stable operating conditions, onset temperature and the cool-down process are studied. Fig. 3 shows the curve of the onset temperature. Quite different from the calculated heating block temperature in stable

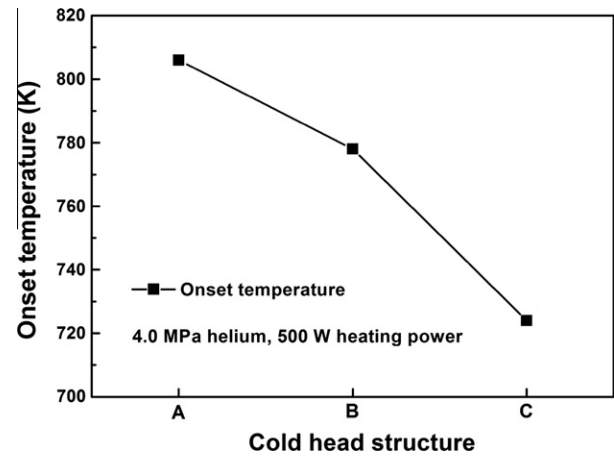


Fig. 3. Curve of the onset temperature.

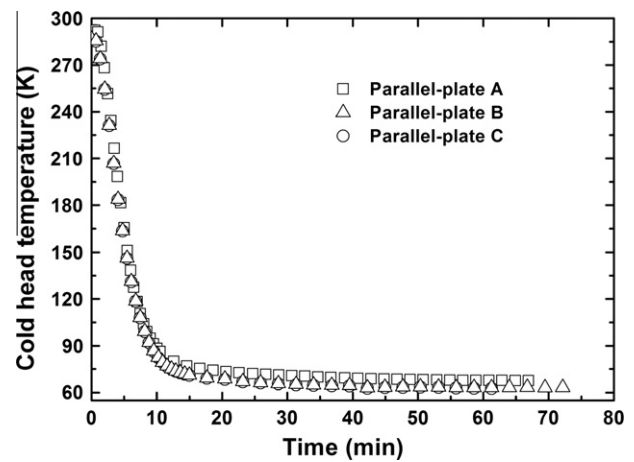


Fig. 4. Cool-down process (4.0 MPa helium, 500 W heating power).

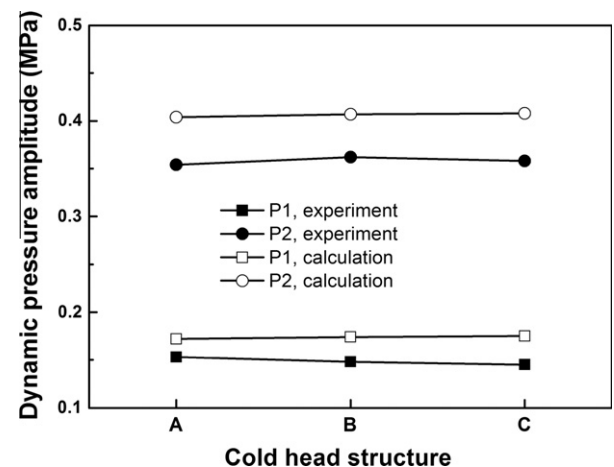


Fig. 5. Comparison between experiments and calculations on dynamic pressure amplitudes at P_1 and P_2 (4.0 MPa helium, 500 W heating power).

operation, the difference of the onset temperature among these three cold heads is much larger. System with parallel-plate C cold head has the lowest onset temperature of 723 K. With respect to the cool-down curves as displayed in Fig. 4, except for the stable no-load cold head temperature, the cool-down processes are very similar.

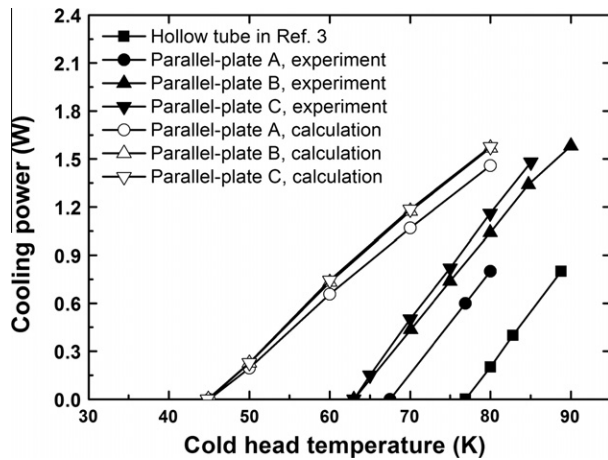


Fig. 6. Comparison between experiments and calculations on net cooling power of the PTC (stand-alone simulation of the PTC with the same P_2 as the experiments).

Table 5

Comparison between experiments on PTC with hollow tube cold head and parallel-plate cold head (4.0 MPa helium and 500 W heating power).

	P_2 (MPa)	No-load T_c (K)	Cooling power at 80 K (W)
Hollow tube in Ref. [3]	0.38	76.9	0.20
Parallel-plate	0.35	63.0	1.16

Fig. 5 shows the curves of the pressure amplitudes at both ends of the APAT. For these two variables, the calculations agree relatively well with the experiments. The difference is about 10%. However, this difference of pressure amplitude at the inlet of the PTC (i.e. P_2) would lead to a larger calculated acoustic work and cooling power. Therefore, for a fair evaluation, stand-alone calculation of the PTC performance has been carried out with the same P_2 as that of the experiments. As illustrated in Fig. 6, the deviation is quite large. The predicted no-load cold head temperature is lower than the experimental temperature by about 18 K, while the calculated cooling power at 80 K is about one and a half times as large as the corresponding experimental cooling power. This big divergence might be attributed to the idealized cold head configuration in the model and other model discrepancies. In addition, flow mal-distribution due to the asymmetrical flow channel arrangement of the cold head structure might also contribute to the discrepancy.

So far, the largest achievable cooling power at 80 K is 1.16 W with the heating power being 500 W. Once experimentally increasing the heating power to 600 W and keeping the heating block temperature within the safe operation limit, i.e. 923 K, a lowest temperature of 60.5 K has been achieved with parallel-plate cold head C, which is to our knowledge the lowest recorded temperature ever reported on such high frequency thermoacoustically-driven single stage PTC.

Table 5 lists a comparison between experiments on systems with hollow tube cold head [3] and parallel-plate cold head C. With the application of the parallel-plate cold head, the no-load cold head temperature decreases from 76.9 K to 63 K, and the cooling

power at 80 K is almost six times as large as that obtained in our former experiments, demonstrating the important role of cold head structure in the HFTAPTC performance.

4. Conclusions

Low thermal efficiency presents as one of the main obstacles preventing the HFTAPTC from practical applications. In order to improve the thermal efficiency of a 300 Hz SWTE driven PTC to be comparable to that of a 50 Hz PTC, the influences of cold head structures were studied both numerically and experimentally in this work. A reasonable agreement has been reached. The results demonstrate that the cold head structures have almost no impact on the heating block temperature and the inlet pressure amplitude into the PTC but have great impact on the cooling power. Among the optional cold head structures, system with parallel-plate cold head whose flow channel width is 0.1 mm and gas–solid heat exchange area is 529.1 mm², achieves a lowest no-load temperature of 63 K and a maximum cooling power of 1.16 W at 80 K experimentally, indicating a great improvement over the previous work. Further work would focus on the reduction of the large deviation between experimental and calculated no-load cold head temperature and cooling power. In addition, a novel regenerator structure for the high frequency PTC would also be studied.

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